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ABSTRACT

The accepted paradigm in aerospace systems design was to design systems sequentially and iteratively to maximize performance based on minimum weight. The traditional paradigm does not work in the rapidly changing global environment. A paradigm shift from the norm of "design for performance" to "design for affordability and quality" has been occurring in recent decades to respond to the changing global environment. Observations were made regarding new tenets needed to bridge the gap from the old to the new. These tenets include new methods and techniques for designing complex systems due to uncertainty and mulit-dimensionality, consideration of the life cycle of the system, and the methods needed to assess breakthrough technologies to meet aggressive goals of the future. The Technology Identification, Evaluation, and Selection method was proposed as a possible solution to the paradigm shift. In particular, refinements of selection approaches were presented and included scoring models, technology frontiers, and resource allocation. Each of the approaches provided a different viewpoint of the same problem of selecting the best mix of technologies to maximize customer satisfaction. The new elements of the selection step were applied to a High Speed Civil Transport concept. This concept was chosen due to the technically challenging customer requirements and the need for breakthrough technologies over present capabilities. The new selection approaches deemed three technologies worthy of scarce resource monies for further development and include composite fuselage structures, hybrid laminar flow control, and advanced flight deck systems, such as synthetic vision. Finally, to meet imposed noise regulations, an advanced engine concept must also be pursued to ensure compliance with FAA regulations.

INTRODUCTION

In 1962, Thomas Kuhn wrote *The Structure of Scientific Revolutions*. In this work, Kuhn [1] argued that science does not progress in a steady, cumulative acquisition of knowledge "from lesser to greater truth, but remains fixated on a particular dogma or explanation – a paradigm."[2] A paradigm is essentially a collection of beliefs, theories, standards, and methods shared by scientists that guides research efforts. Scientists accept this paradigm to be self-evident and "try to extend its scope by refining theories, explaining puzzling data, and establishing more precise measures of standards and phenomena".[3] Yet, with any paradigm, a revolution eventually occurs that may expose the inadequacies of the current paradigm. When this occurs, the crisis "can only be resolved by an intellectual revolution that replaces the old paradigm with a new one."[3] This phenomenon is called a *paradigm shift*. "A shift in the paradigm alters the fundamental concepts underlying research and inspires new standards of evidence, new research techniques, and new pathways of theory and experiment [3]" that are drastically different from the old tenets. A paradigm shift has been occurring in the aerospace industry for the past two decades. The accepted paradigm is to design systems sequentially and iteratively to maximize performance based on minimum weight with cost and quality as a by-product. This school of thought does not work in the rapidly changing, global environment. To satisfy the demanding requirements of future systems, change is needed.

CHANGING GLOBAL ENVRIONMENT - The impetus for the paradigm shift in the aerospace industry is due to the changing global environment. The shift is based on a multitude of contributing factors including the fervour for higher return on investment (ROI), reduced spending budgets, increased system complexity, changing federal and international regulations, projected commercial traffic growth, and the desires of the travelling public for comfort, safety, and affordability [4]. Each factor has contributed to the need for a change in the manner in which aerospace systems are designed. The *paradigm shift* is from "design for performance" to "design for affordability and quality".

THE NEED FOR CHANGE: A PARADIGM SHIFT - Many have observed the means by which the transition from the old to the new paradigm may occur. In particular, the current NASA administration has noticed this shift in aviation focus and responded with the "Three Pillars for Success" program. *"To preserve our Nation's economic health and the welfare of the traveling public, NASA must provide high-risk technology advances for safer, cleaner, quieter, and more affordable air travel."* [5] This quote is one pillar of NASA's "Three Pillars for Success" program. This program was designed to be a roadmap to focus U.S. aerospace endeavors for the next 20 years in accordance with the changing environment of future aviation. Another pillar was revolutionary technology leaps. "An enabling technology goal … is to provide next-generation design tools (and methods)...to increase design confidence, and cut the development cycle time for aircraft in half".[5] Long-term goals have been set for percent reductions in the paradigm shift factors (affordability, safety, etc.) for next-generation vehicle concepts. For example, the affordability goal is to reduce the cost of air travel by 25% in the next 10 years and 50% in the next 25 years. To overcome this challenge, technological breakthroughs need to be identified and developed to achieve the cost savings not possible through evolutionary improvements [6], where an evolutionary improvement is an incremental change in performance. Further, Mavris, et. al. noted that the future requirements call for solutions that are outside of the traditional, historical/evolutionary databases, while maintaining the importance of safe and affordable technology, and demanding the consideration of all life cycle associated implications [7]. Three underlying themes are evident to meet the goals of the future and to establish the new paradigm: life cycle considerations, new methods, and technological breakthroughs.

1) *Why is consideration of the life cycle of a system important*? The life cycle phases of an aircraft include conceptual, preliminary, and detailed design, production, service, and retirement. Each of these phases has a considerable impact on the aircraft system in question. In particular, there is a strong "cost-knowledge-freedom" dependency from conceptual design to production, which can significantly impact the entire life cycle of a system, specifically cost and quality, or customer satisfaction. As the design progress from conceptual to production in tradition design approaches, the design freedom rapidly decreases, while the knowledge about the design slowly increases, and the majority of life cycle costs committed gets locked in early [7]. The most freedom for the decision-maker exists in the conceptual phase and the beginning stages of the preliminary phase before a configuration is "frozen" and detailed design commences. Hence, making educated decisions (increased knowledge) early on, and maintaining the ability to carry along a family of alternatives (design freedom leverage) without locking in costs is the key to success of the paradigm shift [7]. Essentially, new methods are needed to bring information and issues associated with later phases forward and reduce committed costs by maintaining design openness.

2) *What are the fundamental reasons for new methods*? The answer is two-fold: modern design is probabilistic in nature and the evaluation criterion is multi-dimensional rather than the traditional single objective of maximizing performance based on minimum weight. Uncertainty may defined as a potential deficiency that is due to lack of complete knowledge, or a difference between reality and what is expected, and may be represented by a probability distributions [8]. Uncertainty also arises from various contributing factors including ambiguous customer requirements, analysis tool fidelity, manufacturing tolerances, daily fuel costs, etc.[9,10] Traditionally, uncertainty in knowledge about structural loads, mathematical models, economic assumptions, potential technological risks, etc., has been simulated deterministically through factors of safety and assumptions of reality [11]. This is the poor man's way of handling uncertainty. The more appropriate method is to incorporate mathematical models of probability and statistics to account for uncertainty in a more rigorous fashion. Many fields have taken this approach including structural reliability design, economic theory, and meteorology. Based on this rationale, the evolving modern aircraft design *must be* probabilistic in nature rather than the traditional deterministic approach.

The multi-dimensionality of the evaluation of new systems is intuitive. As with any complex system, there is no single, exclusive customer or overall objective. For aircraft systems, the customers included all parties inherently associated with the design, operation, use, and regulation of the aircraft: airframe and engine manufacturers, regulatory entities, airlines, airports, and passengers. Thus, new methods for evaluating designs are needed that can capture the multiple, usually conflicting, objectives (or criteria) to identify design alternatives that may "best" satisfy all criteria. Further in the context of design decision-making, criteria are customer supplied guidelines that form the bases for the decision-making process. The balancing of these objectives is paramount to the success of the design since the design outcome depends heavily on the preference ordering of the criteria and may produce drastically different design solutions [12].

3) *Why are breakthrough technologies needed*? A recent National Research Council report urges that to achieve the goals set forth in the "Three Pillars for Success" program and to respond to the changing global environment, breakthrough technological capabilities, both evolutionary and revolutionary, will be required [13]. Yet, the adaptation by manufacturers or operators of new technologies, which are not incremental or imposed by regulation, encounters strong opposition, since both are driven by economic incentives, conventional or existing technologies are usually preferred [13]. However, Bandte observes that "current technology is readily available for implementation in the system. Yet, it may be obsolete when the system is actually fielded."[12] In general, commercial aerospace systems require 8 to 15 years from concept formulation until product launch. Hence, if a system is to be designed with current levels of technology, when the system is introduced 15 years down the road, the technologies *will be obsolete*. "New technological solutions have to be found, applied to the components, and incorporated into the system."[12] This must be considered in the beginning phases of design since the impact of adding technologies later on in the process will require a redesign of the existing system and significant cost implications. "But these technological solutions may only be at a conceptual stage in their development (and) several questions remain concerning the readiness for implementation when needed and the actual performance level once implemented."[12]

Two issues arise from this discussion. First, significant technological breakthroughs are required to meet future customer requirements. Yet these technologies are more than likely immature when the initial feasibility studies of a concept are conducted. Thus, the primary impact that an immature technology may have on the system when it is entered into service is *uncertain* and must be estimated. Second, a typical design process takes a minimum of 8 years before service begins. Therefore, to include immature technologies in the conceptual phase, the decision-maker must have some means of predicting how the technology will impact the system in the future and what is required to mature the technology. A technology forecast must be made.

Technology forecasting is a prediction of the future characteristics (performance levels such as speed or power) of useful machines, procedures, or techniques [14]. Forecasting does not eliminate uncertainty, but helps to reduce it; thereby providing a better view of the future and the evolutionary path that was followed so as to lead to more informed decisions [15]. Technology forecasting started in 1959 with Lenz's Master's thesis. Only in the late 1960's did it get attention due to attempts to control the mushrooming growth and planning in R&D".[16]

The question now at hand is what tenets constitute the new paradigm. What system and what technologies in how long, for how much, and at what risk? In other words, a rapid, systematic, and methodical forecasting method or environment is needed which can quantify next-generation concept performance, economic and risk aspects and compare these results to future goals. The method must be efficient to reduce design time while capturing the impact of design decisions on the affordability of a vehicle system. This method must account for multiple objectives and constraints in the presence of operational and economic uncertainty, requirement ambiguity, and conflicting objectives. Furthermore, the process must allow for the infusion and subsequent affordability assessment of new technologies while considering technological and economic risk.

METHODOLOGY

The Technology Identification, Evaluation, and Selection (TIES) method responds to the paradigm shift in aerospace systems design and is shown as an eight step process in Figure 1. The steps are shown as the boxes on the primary axis from "Define the Problem" to "Technology Selection". Above the axis are the inputs or techniques required or used to accomplish each step. Below the axis are the primary results from the execution of each step. TIES has been described in detail in Reference [17] for the selection of the best family of technology alternatives without uncertainty. And in Reference [18], where the selection process was performed with the inclusion of technological uncertainty, measured as a function of technology readiness level (TRL) [13]. TRL is a NASA defined metric that qualitatively describes the major milestones of a technology development program achieved from concept formulation to widespread adoption [18]. Herein, the latest TIES developments are described and implemented. In particular, Step 8 – "Technology Selection" – has been enhanced from previous work.

SUMMARY OF STEPS 1 THROUGH 7 – TIES begins with the definition of the problem through a mapping of the customer requirements into quantitative evaluation criteria, system metrics. Next, a potential class of vehicle concepts, e.g. a high capacity, long range, subsonic transport class, is identified that may fulfill the customer requirements. A functional decomposition of the class of vehicle is performed via a Morphological Matrix [15] to identify concept alternatives. From this matrix, a baseline vehicle is established. A design space, bounded by control variables such as wing aspect ratio, engine thrust, etc. is defined for the baseline. This space is investigated for system feasibility in a Modeling and Simulation environment via the Response Surface Methodology and/or the Fast Probability Integration

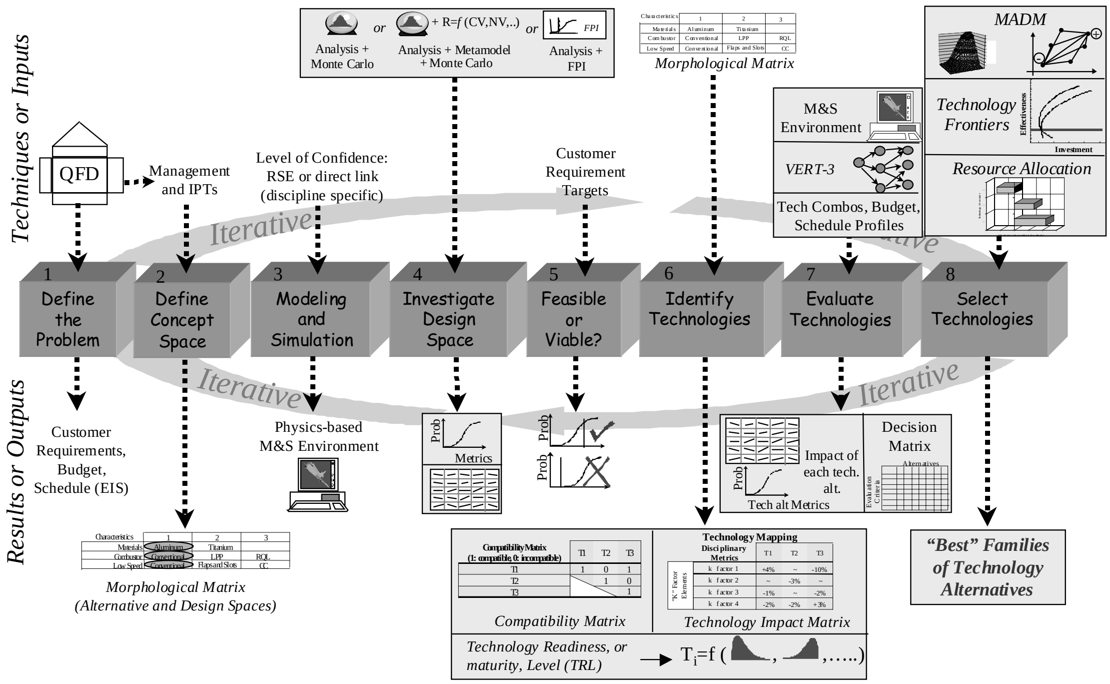

Figure 1: Technology Identification, Evaluation, and Selection Method

technique. If the probability of success for system feasibility is unacceptable, the decision-maker has the option to expand the design space, relax the constraints, select a different concept space, or infuse new or alternative technologies. The later option motivates the need for the TIES method. The next step is to identify the technologies to be applied. Within the identification step, the decision-maker must establish the current TRL of each technology for which defines the associated uncertainty, establish physical compatibility rules, and determine the enhancements and degradation to the system from the infusion of the technology, formalized in a Technology Impact Matrix (TIM). Next, the technologies are combined, based on the compatibility rules, and evaluated at a theoretical limit – no uncertainty included - and as subjected to technological uncertainty. The evaluation results include the theoretical limit values and cumulative distribution functions (CDFs) of the impact of the technology mixes on the system metrics which are combined into a decision matrix. The current research focuses on the enhancing the last step, technology selection under uncertainty. The reader is referred to References [10,17,18,19] for more detailed information regarding steps 1 through 7.

STEP 8: TECHNOLOGY SELECTION - For any multi-attribute, -constraint, or –objective problem, the selection of the “best” family of alternatives is inherently subjective and no single answer will fulfill all requirements. Three approaches are proposed to account for the subjectivity of the problem:

1. Scoring Models: Multi-Attribute Decision-Making (MADM) techniques
2. Technology Frontiers: Performance, Economic, and System Effectiveness vs. Investment Costs
3. Resource Allocation: One-to-one technology comparison

Scoring Models - “A popular technique for subjectively evaluating multiple objectives is a scoring model approach. Scoring models are analytical approaches that weight the subjective criteria of an investment decision. For example, scoring models allow the analyst to subjectively incorporate the impact of quality, flexibility, lead time, reliability, schedule stability, and risk on the investment portfolio”.[20] An example of a weighted scoring model approaches are MADM techniques. A abundance of MADM techniques have been created over the past 40 years to aid the decision-maker to identify the best alternative amongst a finite set, while maximizing customer satisfaction with respect to more than one attribute, or criteria [21]. The use of scoring models has many advantages. The implementation is straightforward and easy to understand. Multiple objectives are accommodated with subjective weightings and risk is accounted for through subjective evaluation. Some of the disadvantages of scoring models include that the outputs are not subject to rigorous defense and can only be interpreted as relative measures. The scores have no absolute meaning in themselves and the problems tend to be oversimplified [20].

A scoring model approach can provide a great deal of insight as to how the various concept alternatives compare to one another. One particular technique that is very simple and easy to implement is the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [21]. TOPSIS is based on the notion that the best alternative amongst a finite set should have the shortest distance to the ideal solution and farthest from the negative-ideal solution. TOPSIS provides a preference order of the deterministic values obtained in the decision matrix, at a given confidence level, resulting in a ranking of the best alternative concepts.

TOPSIS begins with the decision matrix (DM) created in Step 7 for "n" criteria and "m" alternatives. TOPSIS is executed in six steps as described by Hwang [21].

$$DM = \begin{array}{c c} & \begin{array}{ccccc} R_1 & \cdots & R_j & \cdots & R_n \end{array} \\ \begin{array}{c} Alt_1 \\ \vdots \\ Alt_i \\ \vdots \\ Alt_m \end{array} & \begin{bmatrix} r_{11} & \cdots & r_{1j} & \cdots & r_{1n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ r_{i1} & \cdots & r_{ij} & \cdots & r_{in} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ r_{m1} & \cdots & r_{mj} & \cdots & r_{mn} \end{bmatrix} \end{array}$$

where Alt_i is the i^{th} alternative, and
r_{ij} is the numerical outcome of the i^{th} alternative with respect to the j^{th} criterion

Step 1: Construct the normalized DM: This step normalizes each criterion to allow for an "apples-to-apples" comparison. Each criterion is divided by the norm of the total outcome vector of the given criterion, such that each criterion vector has the same unit length.

$$x_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}}$$

Step 2: Construct the weighted normalized DM: The subjectivity of the selection process is introduced through weights on each criterion based on the decision-makers preference of importance. The normalized DM is calculated by multiplying each column of the matrix $\mathbf{X}_j$ with its associated weighting factor, w_j. Thus, the weighted normalized DM, **V**, is equal to

$$V = \begin{bmatrix} v_{11} & \cdots & v_{1j} & \cdots & v_{1n} \\ \vdots & & \vdots & & \vdots \\ v_{i1} & \cdots & v_{ij} & \cdots & v_{in} \\ \vdots & & \vdots & & \vdots \\ v_{m1} & \cdots & v_{mj} & \cdots & v_{mn} \end{bmatrix} = \begin{bmatrix} w_1 x_{11} & \cdots & w_j x_{1j} & \cdots & w_n x_{1n} \\ \vdots & & \vdots & & \vdots \\ w_1 x_{i1} & \cdots & w_j x_{ij} & \cdots & w_n x_{in} \\ \vdots & & \vdots & & \vdots \\ w_1 x_{m1} & \cdots & w_j x_{mj} & \cdots & w_n x_{mn} \end{bmatrix}$$

Step 3: Determine ideal and negative-ideal solutions: Let two artificial alternatives, A* and A¯, be defined as

$$A^* = \left\{ \left(\max_i v_{ij} \,\middle|\, j \;\; \varepsilon \;\; J \right), \left(\min_i v_{ij} \,\middle|\, j \;\; \varepsilon \;\; J' \right) i = 1,2,...,m \right\}$$
$$= \left\{ v_1^*, v_2^*, ..., v_j^*, ..., v_n^* \right\}$$

$$A^- = \left\{ \left(\min_i v_{ij} \,\middle|\, j \;\; \varepsilon \;\; J \right), \left(\max_i v_{ij} \,\middle|\, j \;\; \varepsilon \;\; J' \right) i = 1,2,...,m \right\}$$
$$= \left\{ v_1^-, v_2^-, ..., v_j^-, ..., v_n^- \right\}$$

where
J = {j = 1,2,…,n | j associated with a benefit criteria}
J' = {j = 1,2,…,n | j associated with a cost criteria}
and "benefit" is an attribute for which maximization is desired and "cost" is an attribute for which minimization is desired. Thus, the two artificial alternatives, A* and A¯, indicate the most preferable alternative (ideal solution) and the least preferable alternative (negative-ideal solution), respectively.

Step 4: Calculate the separation measure: The n-dimensional Euclidean distance calculates the separation, or distance, between each alternative. The separation of each alternative from the ideal solution is given by

$$S_{i*} = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^* \right)^2}, \quad i = 1,2,...,m$$

And, the separation from the negative-ideal solution is given by

$$S_{i-} = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^- \right)^2}, \quad i = 1,2,...,m$$

Step 5: Calculate the relative c*loseness to ideal solution*: The relative closeness of each alternative, Alt_i, with respect to A* is defined as

$$C_{i*} = \frac{S_{i-}}{S_{i*} + S_{i-}}, \qquad 0 < C_{i*} < 1, \qquad i = 1,2,...,m$$

If $C_{i*} = 1$, Alt_i = A* and if $C_{i*} = 0$, Alt_i = A¯. An alternative is closest to A* as C_{i*} approaches 1.

Step 6: Rank the preference order: The ranking of the best alternatives may be determined from a ranking in descending order of C_{i*}.

There are two limitations to TOPSIS. First, TOPSIS requires that deterministic values be used when creating the DM and ranking the alternatives. The technology impacts on the system are probabilistic. Thus, information regarding the different metric CDFs may be lost in the down select process and include the variability that is associated with a given mix of technologies, the costs associated with bringing forth that system, and the time required to do so. Hence, the results of the TOPSIS method should not be the only source for program management. As a simplified approach to overcoming the limitations of TOPSIS, one could select the top alternatives for different confidence levels and weighting scenarios. Once the top alternatives are determined, the results may be compared to conclude if any combinations consistently rank in the top ten or so, regardless of confidence level. Although this is a simple approach, visualizing the impact of uncertainty of the top alternatives is not necessarily intuitive. One should note that the results of the top alternatives for different confidence levels might not be identical due to the fact that the variance of the alternative CDFs change. The variance is driven by the uncertainty associated with an immature technology (low TRL) and *increases when more technologies are added*. Finally, the numerical values obtained from the ranking of alternatives are non-intuitive to the decision-maker, especially for visual representations.

TECHNOLOGY FRONTIERS - The inefficiencies of the scoring model, deterministic and non-intuitive numerical results, may be overcome with the use of *Technology Frontiers*. Technology Frontiers are defined as the limiting threshold of an "effectiveness" parameter, whereby uncertainty is captured and intuitive results presented. The technology frontier takes a similar approach as TOPSIS, but attempts to provide a more intuitive result and ease of visualization. An effectiveness parameter (EP) is a user-defined function for which maximization is desired. As in the case of the scoring models, preference of the different criteria is introduced through weighting factors. Two intuitive effectiveness parameters may be defined as Performance (PE) and Economics (EE). Similar to the "benefit" and "cost" criteria used in TOPSIS, "benefit" and "cost" performance and economics effectiveness parameters are defined, such that:

$$PE^* = \frac{PE}{PE_{Baseline}} \qquad PE^- = \frac{PE_{Baseline}}{PE}$$

$$EE^* = \frac{EE}{EE_{Baseline}} \qquad EE^- = \frac{EE_{Baseline}}{EE}$$

where PE* and EE* are "benefit" and PE^- and EE^- are "cost" effectiveness parameters. $PE_{baseline}$ and $EE_{baseline}$ correspond to datum points for normalization. Creating a PE and an EE for each confidence level of interest captures the uncertainty of the responses and the influence of uncertainty will become clear momentarily. Next, subjectivity is introduced through weights on each criterion based on the decision-makers preference of importance,

$$\overline{w}_{PE^*} = \left(w_{1,PE^*}, w_{2,PE^*}, \ldots, w_{j,PE^*}, \ldots, w_{n,PE^*}\right)$$
$$\overline{w}_{PE^-} = \left(w_{1,PE^-}, w_{2,PE^-}, \ldots, w_{j,PE^-}, \ldots, w_{n',PE^-}\right)$$
$$\sum_{j=1}^{n} w_{j,PE^*} + \sum_{j=1}^{n'} w_{j,PE^-} = 1$$
$$n + n' = N$$

$$\overline{w}_{EE^*} = \left(w_{1,EE^*}, w_{2,EE^*}, \ldots, w_{j,EE^*}, \ldots, w_{m,EE^*}\right)$$
$$\overline{w}_{EE^-} = \left(w_{1,EE^-}, w_{2,EE^-}, \ldots, w_{j,EE^-}, \ldots, w_{m',EE^-}\right)$$
$$\sum_{j=1}^{m} w_{j,EE^*} + \sum_{j=1}^{m'} w_{j,EE^-} = 1$$
$$m + m' = M$$

Where "N" is the number of performance criteria and "M" is the number of economic criteria. Such that the total system performance and economic effectiveness for a given alternative, Alt_i, are defined as

$$PE_{Alt_i} = \sum_{j=1}^{n} w_{j,PE^*} PE_i^* + \sum_{j=1}^{n'} w_{j,PE^-} PE_i^-$$
$$EE_{Alt_i} = \sum_{j=1}^{m} w_{j,EE^*} EE_i^* + \sum_{j=1}^{m'} w_{j,EE^-} EE_i^-$$

The system effectiveness for a given alternative, SE_{Alti}, is a summation of the PE_{Alti} and the EE_{Alti} with subjective weights placed on each parameter:

$$SE_{Alt_i} = w_{perf} PE_{Alt_i} + (1 - w_{perf}) EE_{Alt_i}$$

Once the EPs are determined for each alternative, the technology space may be compared to any parameter of interest. One of particular importance is the investment costs associated with developing a given technology combination to maturity as depicted in Figure 2. A similar approach that was used in TOPISIS for defining the ideal solution is used for the EP of the technology space. A "best compromise" solution may be established based on the technology alternative that is closest to the ideal solution. Finally, the Technology Frontier is established by placing a threshold curve around all of the alternative EPs. The frontier implies that no alternative falls outside of the established boundary.

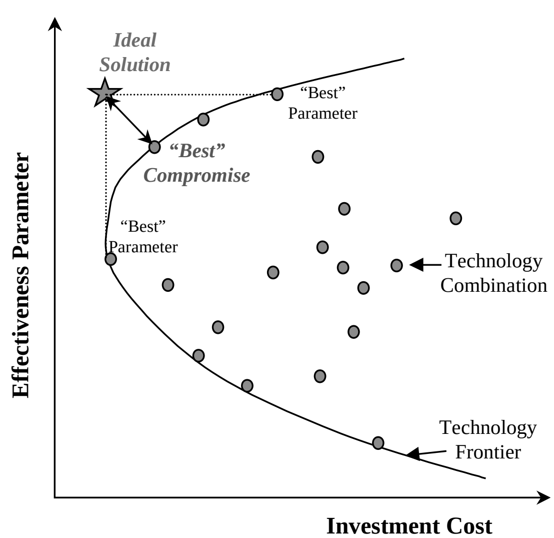

Figure 2: Example Technology Frontier

How will the Technology Frontier change for different levels of confidence? Assessing a technology combination without uncertainty yields the theoretical limit of the technology impact as shown in Figure 3. If the EP is determined for each technology alternative based on this point, then the theoretical technology frontier is defined. Similarly, different frontiers may be established for different confidence levels. As a result, the technology frontiers for increasing confidence levels tighten and produce a smaller technology space. Further, the ideal solution also shifts and reduces the EP magnitude while increasing the investment costs.

To identify the technology alternatives that may satisfy the customer requirements, or criteria, effectiveness thresholds must be established. The effectiveness threshold defines how much improvement is needed from each criterion to create a feasible space. A simplified means by which thresholds can be defined are based on the original PE and EE definitions. In lieu of the technology alternative being used, the target values of the criteria are used, such that

$$PE^{*}_{limit} = \frac{PE_{Target}}{PE_{Baseline}} \qquad PE^{-}_{limit} = \frac{PE_{Baseline}}{PE_{Target}}$$

$$EE^{*}_{limit} = \frac{EE_{Target}}{EE_{Baseline}} \qquad EE^{-}_{limit} = \frac{EE_{Baseline}}{EE_{Target}}$$

If the baseline meets the criteria target value, the effectiveness parameter is set to 1 avoiding an artificial reduction of the threshold limit. The PE and EE thresholds become

$$PE_{threshold} = \sum_{j=1}^{n} w_{j,PE^*} PE^{*}_{limit} + \sum_{j=1}^{n'} w_{j,PE^-} PE^{-}_{limit}$$

$$EE_{threshold} = \sum_{j=1}^{m} w_{j,EE^*} EE^{*}_{limit} + \sum_{j=1}^{m'} w_{j,EE^-} EE^{-}_{limit}$$

and the threshold for the system effectiveness is

$$SE_{threshold} = w_{perf} PE_{threshold} + (1 - w_{perf}) EE_{threshold}$$

Once the threshold for the EP are defined, the values can be overlaid as a constraint on the technology frontier plots, as shown in Figure 4, in addition to a budget limit on the investment monies available. The two threshold limits define the feasible technology space with respect to performance, economics, and the entire system. The technology alternatives that fall within this region are easily identified and may be further investigated. If no alternatives fall within this region, then no technology combinations can meet the imposed customer requirements. Yet, the combinations that come closest to the feasible region may be readily identified. For example in Figure 4, the combination of T3+T7+T9 is very close to the feasible range. A slight reduction in investment expenditures will make this combination

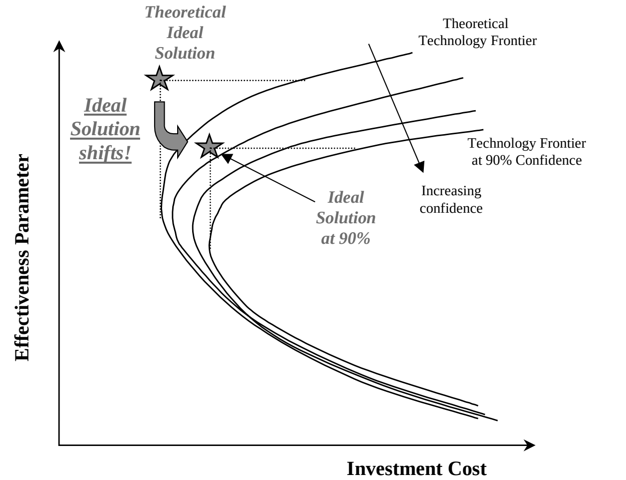

Figure 3: Example Probabilistic Technology Frontier

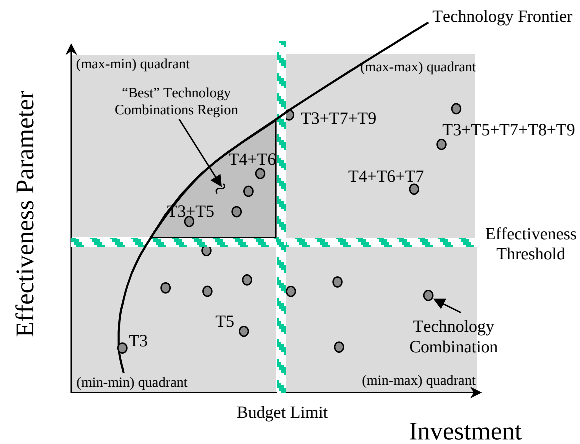

Figure 4: "Best" Technology Combination Region

feasible. The decision-maker may re-evaluate the development schedule of the three technologies to determine if costs savings can be achieved. Technology frontiers provide a rapid and visual means of selecting a family of feasible alternatives.

RESOURCE ALLOCATION - The scoring model and the technology frontier approaches to selecting combinations of technologies to satisfy a set of customer requirements are not the only means by which the alternatives are selected. The final approach is a quantitative resource allocation investigation. From the first two approaches, a family of alternatives are identified that may satisfy the customer requirements with an associated confidence. In general, the more technologies added, the better the performance of the system. Yet, it is highly unlikely that a company has the expendable Research and Development (R&D) budget and resources to develop more than one or two technologies at a time. Thus, a decision-maker desires guidance as to which technology programs should be pursued so that scarce resources may be allocated in an optimal fashion. Unlike the traditional methods of resource allocation, the approach taken here is more rigorous and quantitative, such that decisions made regarding a particular technology development may be justified and tracked. Froham summarizes that traditional R&D projects allocate resources based on past activity in the specific research area rather than the potential bottom line contributions. In addition, far-term thinking and planning is not generally the trend. Short-term funding tends to be the driver for allocating resources which leads to project and endeavors that are not broader-range or do not have long term payoffs for the particular company [22]. The approach herein attempts to deal with these shortcomings. The key aspect of this approach is that the “big hitter” technologies are rapidly and efficiently identified and provide quantitative justification of technology investment program decisions.

The execution of this approach is nothing more than a manipulation of data that was generated in previous steps. In particular, the individual probabilistic technology evaluations are reorganized in a more insightful manner. This is performed through a comparison of the individual technology impacts to the conventional configuration and assessment of the relative change in metrics. The decision-maker would select a particular confidence level and calculate the difference of the alternative’s value as compared to the baseline, resulting in a Δ% metric from the baseline. This can be done for each metric and technology for different confidence levels.

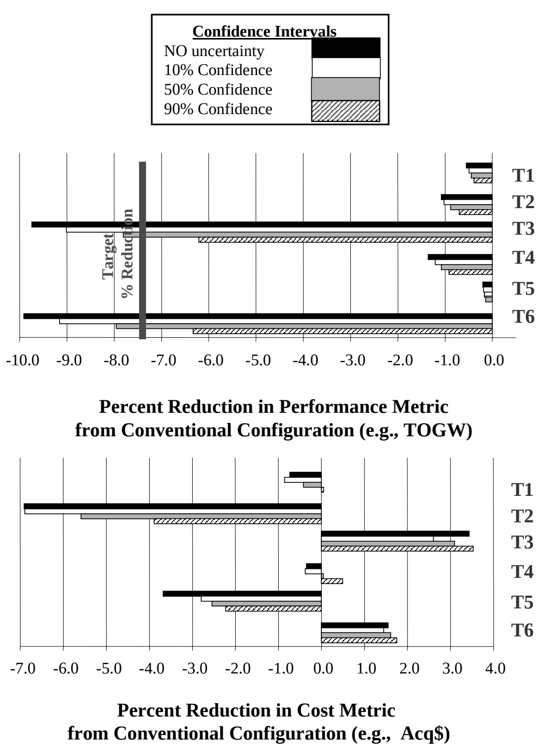

Figure 5: Comparison of Different Metrics for Resource Allocation

However, what may be good for one metric will surely degrade another. For example, consider a performance and a cost metric, both of which a minimum is desired as shown in Figure 5. For the performance metric, a target percent reduction needed from the conventional configuration to obtain a feasible concept is 7.5%, as shown by the vertical line. Both T3 and T6 provide the needed reduction with a confidence level of approximately 65%. Hence, either one of these technologies would be prime targets for increased R&D resources. Yet, one must also consider the impact of a technology on the affordability and other performance metrics of the system. T3 and T6 increase the cost metric relative to the conventional configuration, and could potentially hinder the success of the program. To the decision-maker, the further development of T3 should be in question, unless another technology was infused countering the negative economic impact. One example would be T2. This technology counters the large negative impact of T3 by reducing both metrics. This process is repeated until a handful of technologies are deemed worthy for investment resources.

A FINAL SOLUTION? - The design of any complex, multi-attribute system is highly subjective, especially in the early phases of the development. Thus, the selection of a single concept alternative is highly dependent on the decision-maker’s judgement and the relative importance of the evaluation criteria. Thus, the alternative concepts that have been identified through the selection step should be carried through the design process as long as possible to allow for more design freedom. This entails a re-investigation of the design space with various technology alternatives to establish if a different geometry will increase system feasibility.

IMPLEMENTATION

The Technology Identification, Evaluation, and Selection (TIES) method was applied to a High Speed Civil Transport (HSCT). This concept has received world-wide attention since its renewed interest in the commercial industry in the mid-1980’s. This vehicle was a perfect test-bed for the TIES method due to the technically challenging customer requirements and the need for revolutionary advances over present day capabilities. The results from the investigations in References [17,18] are utilized herein and presented when needed for clarity. From Reference [17], a design space for a conventional HSCT configuration was deemed non-existent due to the violation of the Sideline Noise constraint. The metrics by which system feasibility was measured are listed in Table I. In Reference [18], 11 technology concepts were identified for infusion and are shown as the TIM in Figure 6. The technical “k” factor elements are the anticipated enhancements and degradations to the system from a given technology.

Table I: HSCT System Metrics

Parameter	Acronym	Target or Constraint	Units
Performance			
Approach Speed	Vapp	≤ 106	kts
FAR Stage II Flyover Noise	FON	≤ 155	EPNLdb
Landing Field Length	LdgFL	≤ 11,000	Ft
FAR Stage II Sideline Noise	SLN	≤ 103	EPNLdb
Takeoff Field Length	TOFL	≤ 11,000	Ft
Takeoff Gross Weight	TOGW	≤ 1,000,000	Lbs
Economics			
Acquisition Price	Acq $	*Minimize*	FY96 $M
Research, Development, Testing, and Evaluation	RDT&E	*Minimize*	FY96 $M
Average Required Yield per Revenue Passenger Mile	$/RPM	≤ $0.10	FY96 $M
Total Airplane Related Operating Costs	TAROC	*Minimize*	FY96 $M
Direct Operating Costs plus Interest	DOC+I	*Minimize*	FY96 $M

									Aircraft Morphing		
	Composite Wing	Composite Fuselage	Circulation Control	HLFC	Environmental Engines	Flight Deck Systems	Propulsion Materials	Integrally, Stiffened Aluminum Airframe Structures (wing)	Smart Wing Structures (Active Aeroelastic Control)	Active Flow Control	Acoustic Control
Technical K_Factor Vector	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
Wing Weight	-20%			+5%				-10%	-5%	+2%	
Fuselage Weight		-25%				-15%					
Engine Weight				+1%	+40%		-10%				+5%
Electrical Weight			+5%	+1%		+2%	+5%		+5%	+2%	+2%
Avionics Weight				+5%		+2%	+5%		+2%	+5%	+2%
Surface Controls Weight			-5%						+5%	+5%	
Hydraulics Weight			-5%						+5%		
Noise Suppression					-10%		-1%				-10%
Subsonic Drag	-2%	-2%		-10%						-5%	
Supersonic Drag	-2%	-2%		-15%						-5%	
Subsonic Fuel Flow			+1%	+1%	-2%		-4%				+1%
Supersonic Fuel Flow				+1%	-2%		-4%				
Maximum Lift Coefficient			+15%								
O&S	+2%	+2%	+2%	+2%	+2%		+2%	-2%	+2%	+2%	+1%
RDT&E	+4%	+4%	+2%	+2%	+4%	+2%	+4%		+5%	+5%	+5%
Production costs	+8%	+8%	+3%	+5%	+2%	+1%	+3%	-3%	-3%	-3%	-3%

Figure 6: HSCT Technology Impact Matrix

Table II: Dominant Technology Mixes

Concept	Technology Mix	Concept	Technology Mix
1	T4+T6+T7+T11	6	T2+T4+T5+T7
2	T3+T4+T6+T7+T11	7	T2+T3+T4+T6+T7+T11
3	T2+T4+T7+T11	8	T2+T3+T4+T6+T11
4	T2+T3+T4+T5+T6	9	T2+T3+T4+T5+T6
5	T2+T3+T6+T8+T10+T11	10	T2+T3+T4+T5+T6+T7

For the purpose of technology selection, the decision matrices were populated with the aid of the Pugh Evaluation Matrix technique [23]. Four deterministic Pugh matrices were used and consisted of the deterministic "theoretical" values, and the 10%, 50%, and 90% confidence levels from each alternative metric CDFs. Each matrix was 273 rows by 11 columns, with 273 compatible alternatives and 11 system metrics.

TECHNOLOGY SELECTION - The best alternatives to respond to the customer requirements were established from a balance of the three selection approaches: scoring models, technology frontiers, and resource allocation. The result of each approach is described below.

<u>Scoring Model: TOPISIS</u> - The TOPSIS technique was used on all four Pugh matrices to identify the best mix of technologies to respond to the system metrics in Table I. Each metric was classified as a "cost" since minimization was desired. Furthermore, various weighting factor scenarios were considered in the ranking process, and ranged from heavy performance to evenly distributed. This approached simulated a decision-maker's subjectivity.

Three interesting results were obtained from this approach. First, the top 15 of the 273 technology combinations were compared for each matrix and weighting scenario and an interesting result was acquired. The same 10 combinations ranked in the top 15 regardless of the weighting or confidence level considered. Although the absolute ranking order varied, the same technology mixes appeared. These 10 dominant technology mixes are listed in Table II. At first, this result suggested that a probabilistic assessment might not be needed. Upon further consideration, this was an erroneous conclusion. The ranking of the best technology mixes was relatively consistent since all technologies were approximately at the *same* TRL, i.e., 3 or 4. Hence, the uncertainty assigned to the "k" vector elements was also similar. One could infer that if the TRLs were at different levels for the 11 technologies, the metric CDFs would have different variability.

Next, additional insight was gained from the different weighting scenarios in the form of recurring technologies. In particular, T2, T4, and T6 occurred in eight of the top alternatives. This result would suggest that a composite fuselage, HLFC, and the advanced flight deck systems provided significant benefit with minimal penalty to the performance and economics of the system. Finally, the similarity of the different scenario results indicated that the technology mixes were fairly robust to changes in the decision-makers preference of metric importance.

For a comparison, let an artificial Overall Evaluation Criterion, OEC, be defined for each of the 10 alternatives relative to the baseline as

$$OEC_{Alt} = w_1 \frac{TOGW_{BL}}{TOGW_{Alt}} + w_2 \frac{TOFL_{BL}}{TOFL_{Alt}} + w_3 \frac{LdgFL_{BL}}{LdgFL_{Alt}} + w_4 \frac{Vapp_{BL}}{Vapp_{Alt}} + w_5 \frac{FON_{BL}}{FON_{Alt}} + w_6 \frac{SLN_{BL}}{SLN_{Alt}} + w_7 \frac{\$/RPM_{BL}}{\$/RPM_{Alt}}$$

where each metric is equally weighted and a maximum OEC desired. The OEC was chosen for visualization purposes due to the lack of clarity of the numerical values from TOPSIS. The OEC for each concept in Table II was evaluated for the theoretical limit and each confidence level, as depicted in Figure 7. At any confidence level, the best alternative was the combination of T2+T3+T6+T8+T10+T11, while T2+T3+T4+T5+T6+T7 and T2+T3+T4+T5+T6 switched in rank from 2nd and 3rd, respectively, at confidence levels near 90%. The lowest performing alternative was T2+T4+T5+T7 that provided a minimum of a 6% improvement from the baseline.

Technology Frontiers - The technology frontiers approach was applied to the four Pugh matrices. The performance effectiveness, PE, was defined as a function of TOGW, TOFL, LdgFL, Vapp, FON, and SLN. The economic effectiveness parameter, EE, was defined for Acq $ and $/RPM. The measure of comparison was chosen to be the RDT&E costs associated with a given technology combination for PE, EE, and SE. *RDT&E was chosen as a representative economic parameter since, at present, a capability to predict the investment costs associated with the development of an immature technology does not exist.* All metrics contributing to the EPs were classified as "costs" since minimization was desired. The PE and EE thresholds were defined with an equal weighting preference as

$$PE_{threshold} = \frac{1}{6}\frac{TOGW_{BL}}{750{,}000} + \frac{1}{6}\frac{TOFL_{BL}}{11{,}000} + \frac{1}{6}\frac{LdgFL_{BL}}{11{,}000} + \frac{1}{6}\frac{Vapp_{BL}}{155} + \frac{1}{6}\frac{FON_{BL}}{106} + \frac{1}{6}\frac{SLN_{BL}}{103}$$

$$EE_{threshold} = \frac{1}{2}\frac{Acq\$_{BL}}{175} + \frac{1}{2}\frac{\$/RPM_{BL}}{0.1}$$

where artificial constraints were imposed on TOGW (750,000lbs) and Acq $ ($175M) which resulted in a $PE_{threshold}$ = 1.039, $EE_{threshold}$ = 1.073, and the $SE_{threshold}$ was 1.056. An effectiveness value of 1 was indicative of the baseline value. A value below 1 indicated a decline from the baseline value, while a value greater than 1 indicated an improvement.

For combinations, the maximum number of technologies on any given alternative was 6. The PE was considered first and compared to a given alternative's RDT&E costs. The RDT&E was used as a "representative" cost figure. The PE for the "theoretical" technology impacts is depicted in Figure 8. The alternatives were grouped by how many technologies were contained within the alternative, i.e., 1 to 6 technologies, and plotted with the associated RDT&E costs. The minimum value of RDT&E ($13,799M) and the maximum value of PE (1.257) determined the "ideal" solution. The technology frontier was established from a 4th order approximation.

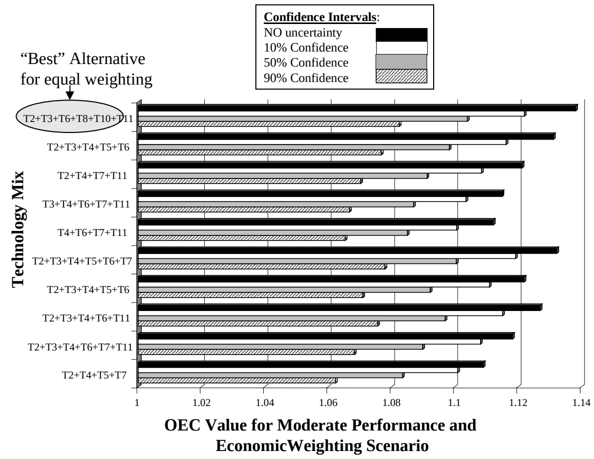

Figure 7: TOPSIS Rankings for Equal Weighting

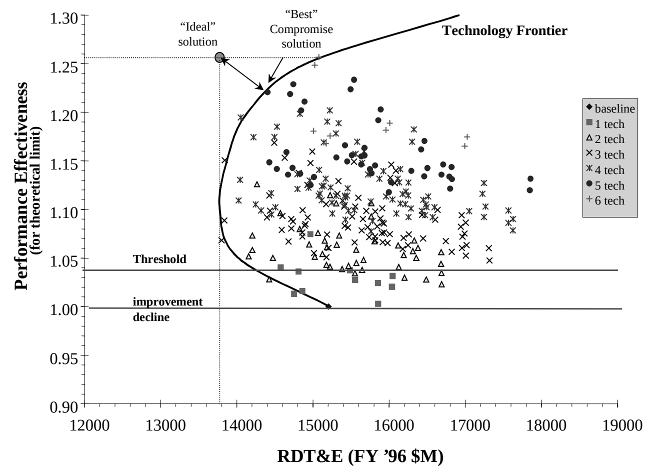

Figure 8: Performance Effectiveness with NO Uncertainty (Theoretical Limit)

A few interesting results were obtained from the "theoretical" technology frontier. First, a clustering of alternatives resulted based on how many technologies were grouped together. All combinations with 1 technology were clustered at low values of PE and had a moderate range of RDT&E. As the number of technologies increased, the clusters increased in PE and varied over a larger range of RDT&E, as evident by the grouping of 5 technologies. This result was anticipated since the addition of more technologies should increase the benefit to the system. Yet, the influence of increased development cost was not evident, since for some combinations with very high PE values, the RDT&E costs were lower. This result can be explained by the dependency of RDT&E on component and system weight. In any cost estimating relationship that is not activity-based, the resulting RDT&E value is directly correlated with weight. Although the relative RDT&E costs was increased through a complexity factor for the different technologies, the increase was countered by a significant reduction in weight. Thus, the decision-maker should take care in selecting the metrics for which EPs are compared. The compromised solution from the "ideal" was T2+T3+T4+T6+T7.

The next comparison was the PE with technological uncertainty included against the RDT&E costs. The 50% confidence level is shown in Figure 9. The introduction of uncertainty reduced the “ideal” solution to 1.197 from the theoretical limit case of 1.257. Also, the ranges of PE values were more condensed than the theoretical case and more alternatives fell below the threshold limit with a lower limit PE of 1. The entire technology space reduced in absolute PE. As a final comparison of the PE, each technology frontier was approximated as a function of RDT&E and compared, in Figure 10. The theoretical limit frontier provided the highest PE value, thus the highest ideal solution. As the confidence level was increased, the ideal solution PE value reduced and the compromised solution changed from T2+T3+T4+T6+T7 to T1+T2+T3+T6. At confidence levels above 50%, the frontiers appeared to converge and become relatively stable on the top portion of the frontier, i.e., higher values of PE. Also, at PE values below 1.1, the confidence levels and the theoretical limit values were not distinguishable. This result implied that the technology combinations that defined the lower portion of the frontier had relatively small variation.

Next, the economic effectiveness (EE) was investigated in a similar fashion as the PE. For brevity purposes, only the final frontiers are shown, but the results for each approach is discussed. For initial insight, the theoretical limit frontier was considered. The threshold was defined with a target value of $0.1 for $/RPM and $175M for the acquisition price (Acq $). The Acq $ was established to be competitive with existing large subsonic transports with which the HSCT would compete. Thus, the EE threshold was 1.073. The impact of this limit on the number of feasible solutions was obvious. Only two combinations, T6+T8+T10 and T6+T8+T10+T11, could surpass the threshold. Yet, the “compromised” solution, T2+T6+T8+T10, fell slightly short of the target value. At this point the decision-maker could increase the target value for the Acq $ price from $175M to $180M to reduce the threshold limit to 1.058. Otherwise, if the Acq $ is a rigid criterion that can not be negotiated, the two alternatives that could exceed the threshold must be chosen, although they are not the “best compromise solutions”. Unlike the PE, the grouping of the number of technologies was more scattered rather than clustered. Further, EE values for approximately half of the combinations considered reduced the EE due to the increased RDT&E, production, and O&S penalties. The alternatives that improved the EE were ones in which significant improvements in the PE were achieved, such that the penalties in cost were countered.

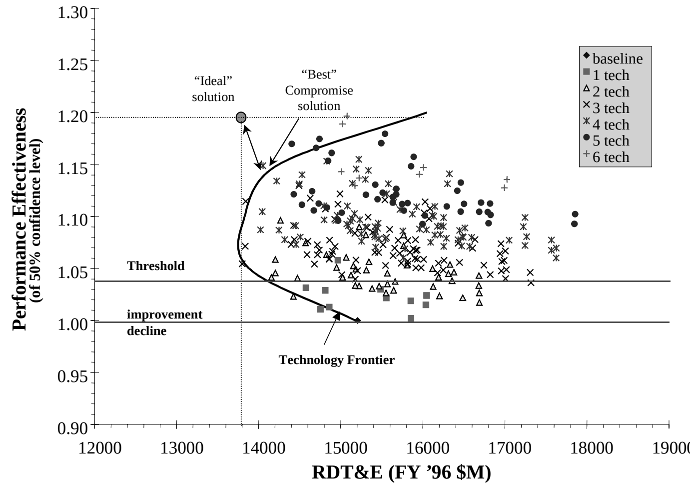

Figure 9: Performance Effectiveness with Uncertainty

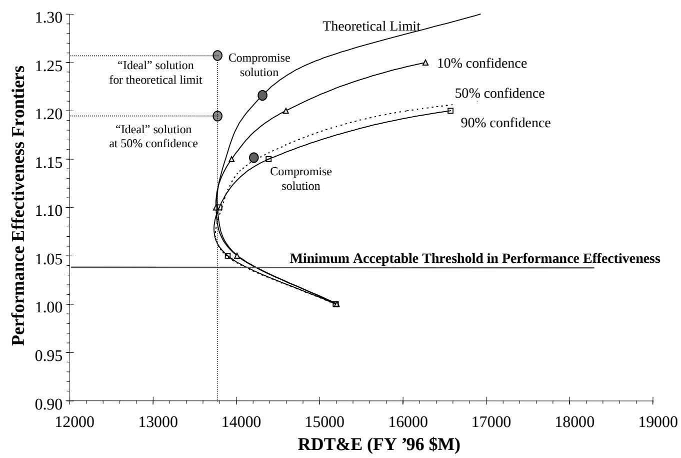

Figure 10: Comparison of Performance Effectiveness at Different Confidence Levels

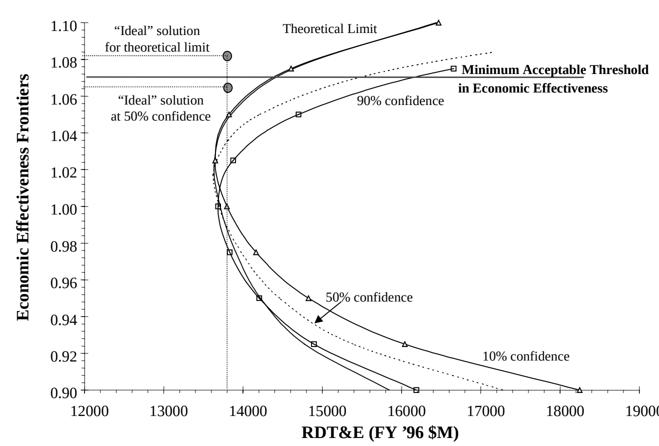

Figure 11: Comparison of Economic Effectiveness at Different Confidence Levels

If the Acq $ target value was rigid at $175M, all alternatives fell below the EE threshold for the 50% confidence level. The compromised solution and the top two performers remained the same as in the theoretical case. As in the PE investigation, the technological uncertainty condensed the frontier space and reduced the ideal solution from 1.082 to 1.064. Again, the decision-maker must make a trade-off as to which technology combination to select.

The four EE frontiers were evaluated to establish the influence of technological uncertainty and compare to the trends of the PE frontiers. The amount of technology space did not decrease as rapidly with the EE uncertainty as with the PE uncertainty at different confidence levels, in Figure 11. The ideal solution reduced and fell below the acceptable threshold for confidence levels above 10%. Unlike the convergence of the PE frontiers at confidence levels above 50%, the EE frontiers converged at low confidence values, <10%, and at EE values >1.025. Furthermore, an EE value of 1.01 appeared to be a pivot point for the frontiers. The condensing of the technology space was minimal, but rotated clockwise. This trend was contrary to the PE of which converged at lower PE values.

For the System Effectiveness (SE) at the four levels at which the technologies were evaluated, an elliptical function was fit to the technology space so that all technology combinations fell within the ellipse as shown in Figure 12. The threshold value for SE was 1.056. As the confidence level was increased, the technology frontier space collapsed to a smaller region. In fact, 40% of the theoretical limit technology space that was above the threshold fell to less than 10% for the 90% confidence level. Hence, increasing confidence to achieve a particular value of system effectiveness reduced the number of options available to the decision-maker, *a very insightful result*. An SE value of 0.97 established a lower limit of which could be considered a "worst" case condition.

Finally, a comparison of the ideal and compromised solution was explored. For each Pugh matrix for which a comparison was made, the ideal and compromised technology solutions are listed in Table III. As was evident in each of the frontier plots, the ideal solution was reduced for increasing confidence levels for all EP. The most prominent technology mixes were T1+T2+T3+T6 (for PE), T2+T6+T8+T10 (for EE), and T2+T3+T4+T6 (for SE). Yet, the EE alternative could not achieve the acceptable EE threshold. The two alternatives that exceeded or were closest to meeting the threshold include T6+T8+T10 and T6+T8+T10+T11.

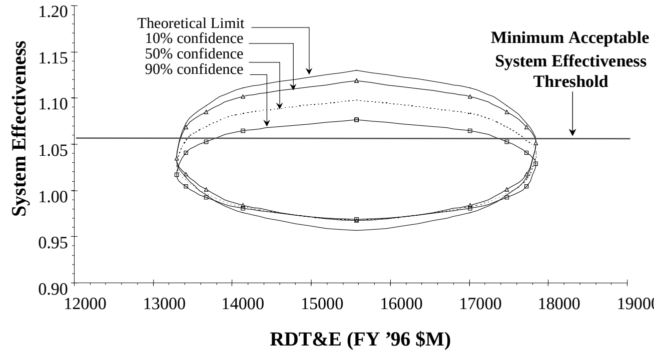

Figure 12: Combined System Effectiveness

Table III: Summary of Best and Compromised Solutions

	PE	EE	SE
Theoretical Limit Ideal Solution	*1.257*	*1.082*	*1.130*
Compromised Technology Solution	T2+T3+T4+ T6+T7	T2+T6+T8+ T10*	T2+T3+T4+ T6
10% Confidence Ideal Solution	*1.220*	*1.072*	*1.119*
Compromised Technology Solution	T1+T2+T3+ T6	T2+T6+T8+ T10*	T2+T3+T4+ T6
50% Confidence Ideal Solution	*1.197*	*1.064*	*1.098*
Compromised Technology Solution	T1+T2+T3+ T6	T2+T6+T8+ T10*	T2+T3+T4+ T6
90% Confidence Ideal Solution	*1.173*	1.055	*1.077*
Compromised Technology Solution	T2+T3+T4+ T6+T7	T2+T6+T8+ T10*	T2+T3+T4+ T6

Resource Allocation - Each of the dominant alternatives in the two previous approaches contained at least four technologies. The risk associated with the undertaking of more than a few technologies concurrently is very high. It is unlikely that a company has the R&D budget and resources to successfully develop more than one or two technologies and would not happen in a real development program. Hence, as a decision-maker, guidance was desired as to which technology would be the most influential for R&D resource allocation to overcome constraints or meet objectives.

A resource allocation investigation was performed by a comparison of the infusion of the individual technologies to the conventional configuration, and evaluation of the deviations in metric values. The SLN and the $/RPM are shown in Figure 13. For the SLN, the target percent reduction needed from the conventional configuration to obtain a feasible concept was 7.28%, as shown by the vertical line. Both engine concepts (T5 and T11) provided the needed reduction with a confidence level of approximately 60%. Hence, either one of the engine concepts would be prime targets for increased R&D resources. Yet, one must also consider the impact of the technology on the system in terms of affordability and other performance metrics. T5 and T11 increased the $/RPM relative to the conventional configuration, and could potentially hinder the success of the program in terms of affordability. In addition, T5 increased the Vapp for all confidence levels to a point where the approach speed constraint of 155 kts was violated by as much as 4.5 kts at the 100% confidence level. T5 negatively impacted all metrics except for FON and SLN. To the decision-maker, the further development of the environmental engines should be in question, unless another technology was infused to counter the negative impact. One example would be the HLFC (T4). This technology counters the negative impact of T5 by reducing all metrics. If a company could invest the resources needed for both technologies, the metrics targets could be achieved. A similar result was obtained for T11, and the same trade-off rationale could be applied to this technology.

As revealed by the TOPSIS approach, T2, T4, and T6 were dominant technologies. In the resource allocation investigation, each of these three technologies reduced all metrics as compared to the conventional configuration, with exception of increased acquisition price for T2 and T4 at all confidence levels. Although none of the technologies could provided the needed SLN reductions, all provide sufficient benefits to other metrics.

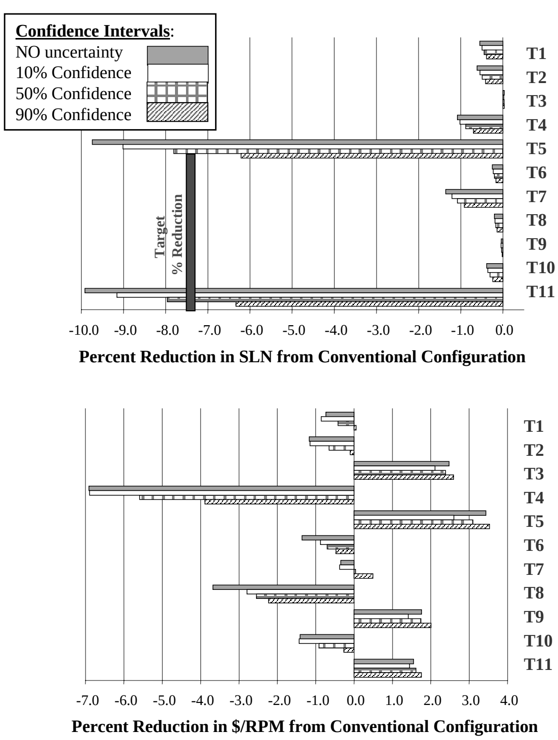

Figure 13: Probabilistic Impact of Technologies on SLN and $/RPM

A FINAL SOLUTION – In the conceptual and preliminary phases, the design of any complex system does not result in a single configuration that maximizes customer satisfaction. This fact is due to the subjectivity of the selection problem and the techniques by which the alternatives are quantified. Thus, three options were posed to provide a cross-section of techniques, while accounting for subjectivity, to identify a family of alternatives that could be further investigated. The three selection approaches resulted in the following "best" alternatives:

Scoring Model:

TOPSIS:

Any combination of T2+T4+T6, while one of the top performers was T2+T3+T6+T8+T10+T11, regardless of inclusion or exclusion of uncertainty

Technology Frontiers:

Performance Effectiveness: T2+T3+T4+T6+T7 with NO uncertainty, while T1+T2+T3+T6 resulted for the inclusion of uncertainty

Economic Effectiveness: T2+T6+T8+T10 with and without uncertainty but did not meet the imposed economic threshold. Only two alternatives could satisfy the threshold at low confidence levels and were T6+T8+T10 and T6+T8+T10+T11

Resource Allocation

Result also showed that T2+T4+T6 were the most significant technologies that improved all system metrics, but SLN could not be met without the addition of an engine concept, such as T5 or T11

From the three selection approaches, 8 technology combinations were considered and are listed in Table IV. Alternatives 1, 5, and 6 do not have an engine technology concept to reduce the noise, yet were prominent when considering all system metrics simultaneously. Hence, these alternatives should drop out of the selection process when considering individual constraints, such as the SLN. For each technology alternative, the level of technology was fixed at the theoretical value and the design space was re-investigated. The level of technology had to be fixed due to the correlation between design variables and technologies, i.e., "k" factors. Correlation of variables implies that the independent variables are directly correlated and cannot be selected independently of each other. A solution is to hold either the configuration or the technologies constant and then iterate to find an optimal solution. This was the approach taken herein.

Steps 4 and 5 were repeated, with the design space defined in Reference [17], for the 8 technology alternatives and the system feasibility quantified. Comparing the amount of feasible space for each alternative revealed that Alternative 3 had the highest percentages than any other considered, as listed in

Table V. In fact, only Alternative 3 and 4 could satisfy all the metric targets. Although Alternative 4 only had a 0.6% feasibility with respect to $/RPM. Alternative 7 had a much higher feasibility for all metrics, except for $/RPM for which there was none.

Recall from the TOPISIS and the resource allocation approaches, T2, T4, and T6 were the most prominent technologies. Again, these three technologies appeared. The only difference between Alternative 3 and 4 was the choice of engine technology concept for noise suppression. Both alternatives substantially improve the SLN, while the $/RPM was moderate. Yet, the design space distributions were much closer to the $0.10 target than the conventional configuration. The conventional configuration design space required at least an 8% improvement in SLN and a 20% improvement in $/RPM to achieve a 25% feasible design space. Alternative 3 achieved more than an 8% reduction in SLN, but only a 7.1% reduction in $/RPM, as shown in Figure 14.

Table IV: "Best" Family of Alternatives

Alternative	Technology Combinations
1*	T6+T8+T10
2	T6+T8+T10+T11
3	T2+T4+T6+T11
4	T2+T4+T5+T6
5*	T1+T2+T3+T6
6*	T2+T3+T4+T6+T7
7	T2+T3+T4+T5+T6+T7
8	T2+T3+T6+T8+T10+T11

Table V: Comparison of Technology Alternatives System Feasibility (% Feasible Space)

Metric (Target)	Conventional	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6	Alternative 7	Alternative 8
TOGW (750,000 lbs)	0	0	0	29.5	19.1	1.6	58.3	45.7	2.9
TOFL (11,000 ft)	4.6	24.9	22.5	8.5	84.8	44	95.2	93.4	51.2
LdgFL (11,000 ft)	90.8	100	99.9	100	100	100	100	100	100
Vapp (155 kts)	4.4	32.2	29.2	97.2	96.2	99.3	100	100	99.1
FON (106 EPNLdB)	0.9	5.8	100	100	100	22.6	95.6	100	100
SLN (103 EPNLdB)	0	0	100	100	100	0	0	100	100
$/RPM ($0.10)	0	0.8	0	2.7	0.6	0	1.0	0	0

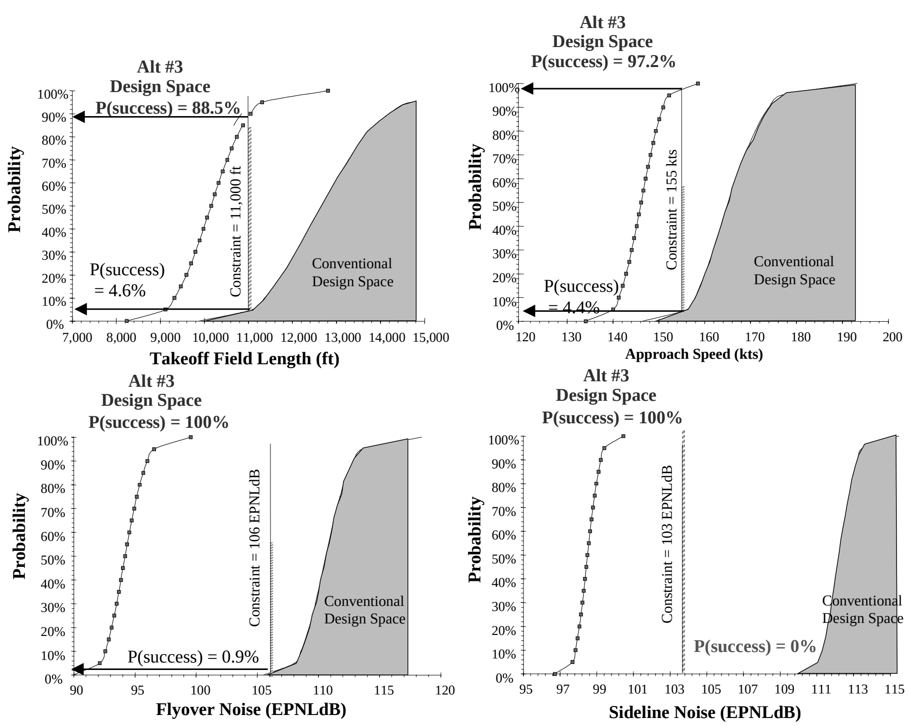

Figure 14: Shift in Design Space for Alternative 3

CONCLUSION

The focus of the current research was to provide various approaches to select the "best" mix of technologies to maximize customer satisfaction. Three approaches were described and included scoring models, technology frontiers, and a quantitative resource allocation investigation. Three approaches were needed to capture the technological uncertainty associated with immature technologies within the selection process and the multidimensionality of design requirements. A proof of concept investigation was performed on a High Speed Civil Transport. This vehicle was used as a test bed due to the technically challenging customer requirements and the need for revolutionary methods to forecast the impact of technological breakthroughs. Three technologies were identified as significant for further investigation and include: composite fuselage structures, Hybrid Laminar Flow Control, and advanced flight deck systems, such as synthetic vision. These technologies were established as prominent from the three selection approaches. An additional investment of an advanced engine concept that could reduce noise characteristics must be pursued to ensure compliance with FAR Stage III noise requirements. A concept containing these technologies could meet all imposed customer requirements and created the most feasible design space for which system trade-offs could occur. The selection approaches are part of a large methodology called Technology Identification, Evaluation, and Selection (TIES). The TIES method is rapid and efficient and may be adjusted for different program assumptions with minimal effort. The techniques that are utilized to build the framework substantially reduce design cycle iteration time and provide quantitative justification for design decisions.

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